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Dynamics of galactic disks in the nonaxisymmetric dark halo

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ABSTRACT

The results of numerical simulations of the dynamics of galactic disks, which are submerged into nonaxisymmetric dark massive halo are discussed. Galaxy disks dynamics in the nonaxisymmetric (triaxial) dark halo were investigated in detail by the high resolution numerical hydrodynamical methods (TVD & SPH) and N-body models. The long-lived two arms spiral structure generates for a wide range of parameters. The spiral structure is global and number of turns can be 2-3 in depends of model parameters. Morphology and kinematics of spiral structures were investigated in depends of the halo and the disk parameters. The spiral structure rotates slowly and the angular velocity varies is quasiperiodic.

1. Dark massive halo and spiral structure

The realistic models of disk galaxies require a massive enough halo. There are the results of numerous estimations of halo mass using various physical approaches [5, 19, 25]. It is essential that the galaxy mass halo and mass of the disk are comparable and frequently, halo mass even exceeds mass of the disk inside of a sphere of optical radius R_{opt} ($R_{opt} \simeq (3-6)\cdot r_d$, r_d — radial exponental scale of stellar disk [43, 20, 18, 21]).

The absence of central symmetry in distribution of mass and potential is a feature of some galactic dark halo [17, 30, 31, 32, 24, 36, 14, 6, 34]. Generally we may consider triaxial halo, oblate or prolate halo [7, 23].

Spiral structure formation in galaxies is important tasks of their physics. There are numerous mechanisms of spiral structure formation such as central stellar bar [35], swing amplification mechanism [4], gravitational instability [22], interactions with another galaxies [38], hydrodynamical instabilities [8], induced star formation in flocculent galaxies [3].

In this work we discuss the possibility of spiral structure formation in disks which are submerged into nonaxisymmetric dark halo (scales a, b, c are different (fig. 1)).

In numerical CDM models dark halo structure significantly differs from central symmetry [1, 2, 7, 11, 23]. Attitude halo scales $q = b/a$, $s = c/a$ can reach 0.5–0.8.

The various observational data indicate a possibility of the triaxial shape of halo. Important markers are

- ◁ Stellar halo objects (RR Lyrae, G,F-dwarfs, SDSS) [17, 30, 31, 40].
- ◁ Tidal streams in Milky Way and in other galaxies (Sagittarius tidal stream, Sagittarius dSph [12, 13], Virgo Over Density [17, 32], The Sagittarius Dwarf Galaxy [24]).
- ◁ Polar Rings [42, 10, 36, 39, 26].
- ◁ Hyper Velocity Stars (HVS) [6, 14, 15].
- ◁ Galactic warps [27].
- ◁ Some features of galaxies structure can give the information about the shape DH [34, 28, 16, 33, 41, 37].

The most important thing for our work is nonaxisymmetric distribution of dark matter in the disk

plane(fig. 1). We will describe this feature by parameter

$$\varepsilon = 1 - \frac{b}{a}\,, \quad (1)$$

which is limited as follows $0 < \varepsilon \lesssim 0.15$. We shall consider the effect of the shape of dark halo on the dynamics of the disk for $\varepsilon > 0$.

2. Dynamical models of stellar and gaseous disks

We have considered dynamics of stellar and gaseous disks in nonaxisymmetric halo separately for stars and gas. The basis of model of collisionless stellar disk is N-body dynamical system and Poisson equation for gravitation:

$$\frac{d^2\vec{r}_i}{dt} = \frac{\partial\Phi}{\partial\vec{r}} + \vec{F}_{halo}(\vec{r}_i, t) + \vec{F}_{bulge}(\vec{r}_i)\,, \qquad i = 1, 2, ..., N \quad (2)$$

$$\Delta\Phi = \frac{\partial}{r\,\partial r}\left(r\,\frac{\partial\Phi}{\partial r}\right) + \frac{\partial^2\Phi}{r^2\,\partial\varphi^2} + \frac{\partial^2\Phi}{\partial z^2} = 4\pi G\varrho\,. \quad (3)$$

In case of gas disk we solve the classical hydrodynamics equations:

$$\frac{\partial\varrho}{\partial t} + \vec{\nabla}(\varrho\vec{\mathbf{u}}) = 0\,, \quad (4)$$

$$\frac{d(\varrho\vec{\mathbf{u}})}{dt} = -\vec{\nabla}P - \varrho\,\vec{\nabla}\Phi_{sum}\,, \quad (5)$$

$$\varrho\frac{d}{dt}\left(\frac{E}{\varrho}\right) - \frac{P}{\varrho}\frac{d\varrho}{dt} = 0\,. \quad (6)$$

We used 2 numerical methods in our simulations:

- TVD MUSCL method
- Lagrangian method SPH with $h \neq$ const (h is kernel scale) [9].

We also used two rigid models of the nonaxisymmetric halo. First is analog of potential of pseudo isothermal halo:

$$\Psi_h(x, y, z) = 4\pi G\varrho_{h0}a^2 \cdot \left\{ \ln(\xi) + \right. \quad (7)$$

$$\left. + \frac{\mathrm{arctg}(\xi)}{\xi} + \frac{1}{2}\ln\frac{1+\xi^2}{\xi^2} \right\}\,,$$

where $\xi = \sqrt{\dfrac{x^2}{a_x^2} + \dfrac{y^2}{a_y^2} + \dfrac{z^2}{a_z^2}}$. In the case of equal values of the scales $a = b = c$, we have a usual model of symmetric pseudo isothermal halo. And the second halo model is analog of model by Navarro, Frenk & White [29]:

$$\varrho_h(x, y, z) = \frac{\varrho_{h0}}{\xi\,(1+\xi)}\,. \quad (8)$$

That kinds of potentials reproduce flat rotation curve with many values of their parameters.

We took into account solid-body rotation of these potentials with angular velocity Ω_{halo}. Halo rotation is slower than rotation of disk on periphery (Ω_{disk}):

$$\Omega_{halo} < \Omega_{disk}(R_{opt})\,. \quad (9)$$

3. Stellar disk dynamics

Our simulations start with axisymmetrical halo $\varepsilon(t = 0) = 0$. Then halo became nonaxisymmetric during some time interval τ, which are 1–3 periods of disk rotation (fig. 2).

In the fig. 6 radial profiles of surface density σ, rotation curve V, dispersion of radial velocities of particles c_r, disk vertical scale are shown for the stellar disk. These distributions ensure the gravitational stability of the disk. Our initial radial distribution is stable because we use Toomre parameter $Q_T = c_r/(3.36G\sigma/\text{æ})$ exceeding 2. All parameters do not change with time in case of axisymmetrical halo (fig. 7).

The situation changes in the case of nonaxisymmetric halo. Fig. 3 show the distributions of the logarithm of the surface density in the disk at different times.

The amplitudes of Fourier-harmonics $m = 2$ at various radii are more complicated. We observe quasiperiodic changes of Fourue-amplitudes for two-arm wave (fig. 4). As the result a rotation velocity of spiral pattern is non-stationary (fig. 5).

Angular velocity of rotation Ω_p is determined by spiral wave phase Θ:

$$\Omega_p = \frac{d\Theta}{dt}\,. \quad (10)$$

Two stages of disk dynamics recognized well. Slow rotation Ω_{p1} related with dynamic of central region and fast rotation Ω_{p2} corresponded with outer disk part.

4. Gaseous disk dynamics

In fig. 8 the typical evolution of a gas disk is shown. It is the logarithm of the surface density

in different times. The formation of two-arm trailing spiral structure is observed. For typical conditions perturbations grow to nonlinear stage during 1-3 circulation and form system of shocks. Analysis of gas flow structure demonstrates it's difficult character. We also observe different shock waves and regions with share flow. Morphology of spiral structures depends on rotation curve $V(r)$, distribution of density in dark halo $\varrho_h(r,\varphi)$, radial distribution of stellar disk density $\sigma(r)$ and the sound speed. Specifically in central part of the disk often liding spirals forms. On periphery this spirals always become lagging spirals. Also liding spirals can produce Θ-like structures (some times nested Θ-like structures, for example see fig.10 with $M = 10$).

Radial profiles of surface density are drawn on fig. 9 for a fixed azimuthal angle. The gas disk responds even to 1 percent of halo non-axisymmetry. We see a small amplitude here. But for 5 percents of non-axisymmetry and more shock waves appear.

Effects of gas temperature on the gas spiral pattern shown in the fig. 10. Different values of the Mach number are used. The circular rotation curves is fixed in these models. The pitch angle of spirals decreases in more cold disk.

Kinematics of spiral pattern in the gas disk is similar to the kinematics of the stellar disk submerged into nonaxisymmetric halo. We observe characteristic quasiperiodic curves like in case of stellar disk.

Effect of selfgravitation increases the efficiency of spiral structure formation by the nonaxisymmetric halo. We simulate only gravitational stable disks. Morphology of waves changing and its amplitude grows.

We also demonstrate formation of similar spiral structures in 2d and 3d numerical simulations (fig.11). Vertical distribution of volume density demonstrate vertical structure of density waves along radius (fig.12). Density waves marked by red arrows and dots at the disk plane (fig.11 down) and also in vertical distribution at the same moment.

5. Discussion and Conclusions

1. Possibility of 2-arms spiral structure formation in the stellar and gas components was shown in case of nonaxisymmetric dark massive halo. Properties of spiral pattern depends on parameters of disk and dark halo.

2. Spiral patterns changes in time.

3. In general the spiral patterns have a similar morphology for 2D and 3D models.

4. The spiral pattern rotates slowly. Position of corotation radius is at the outer part of the disk.

5. A possibility to apply the mechanism consider for the formation of inner spiral structure remains open. It is also possible that the non-axisymmetric halo may explain the outer spiral patterns often observed in HI line and/or in UV (GALEX).

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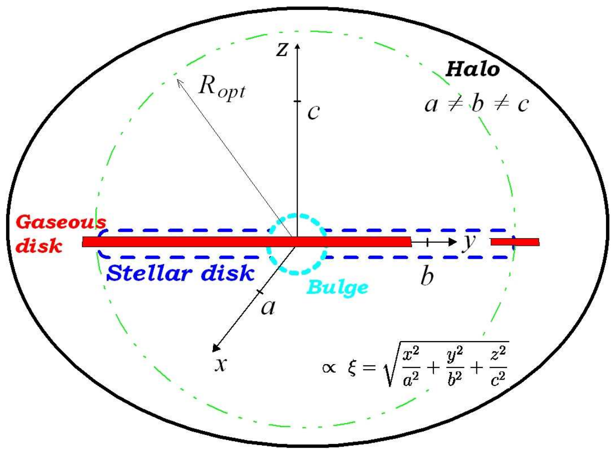


Figure 1: Galaxy disk submerged into triaxial halo

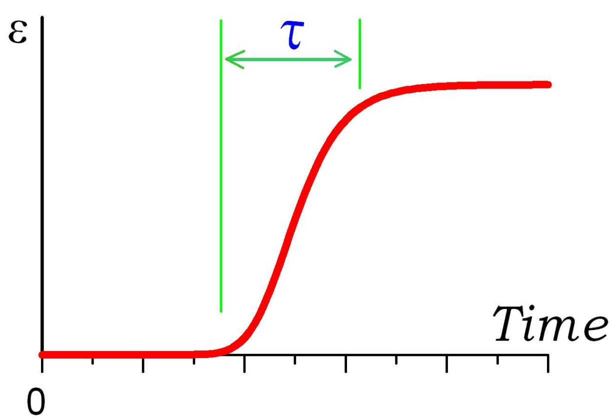


Figure 2: Nonaxissymmetric index as function of time

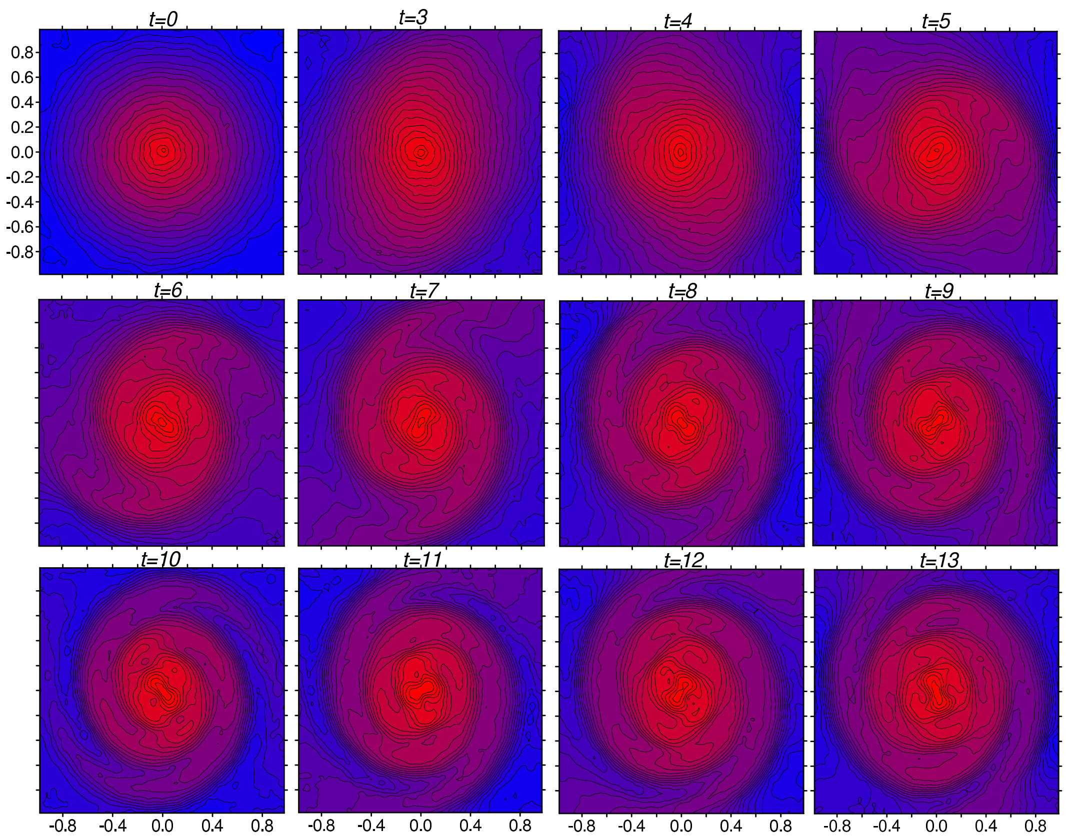


Figure 3: The logarithm of surface density in stellar disk model

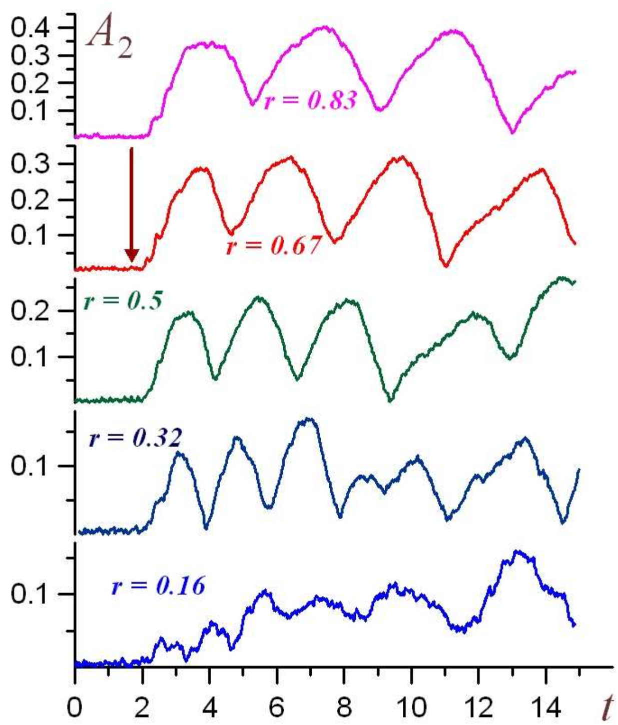


Figure 4: Evolution of Fourier harmonics amplitude for two-arms mode in different radii Value $r = 1$ corresponds $4r_d$.

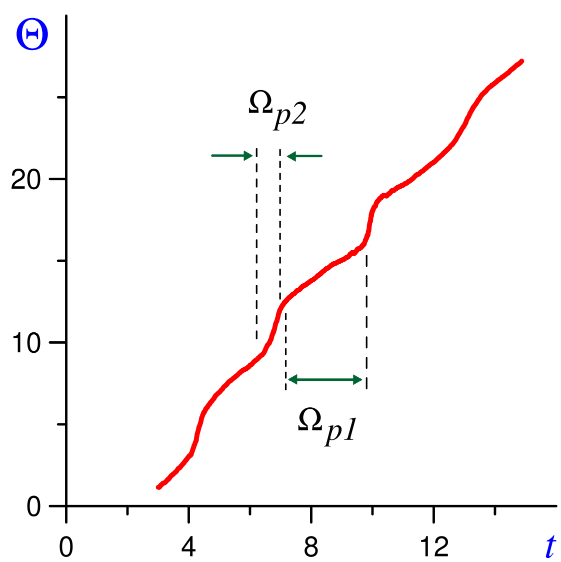


Figure 5: Evolution of Fourier harmonics phase Θ for two-arms mode on fixed radius

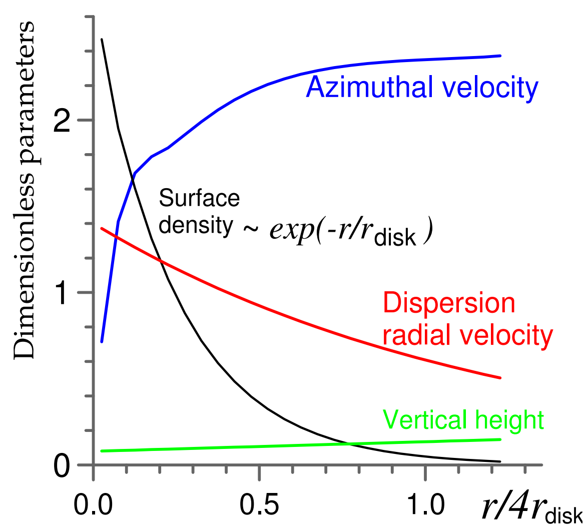
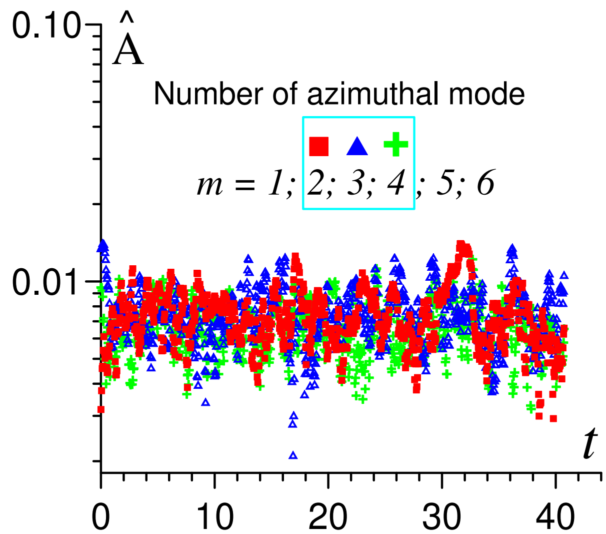


Figure 6: Initial distributions of the basic parameters of the stellar disk



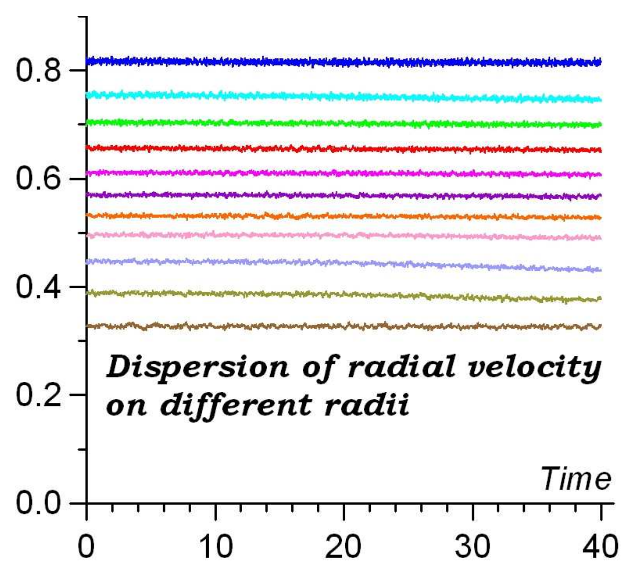


Figure 7: Evolution of stellar disk parameters in model with the axisymmetrical halo are shown. There is no growth of perturbations.

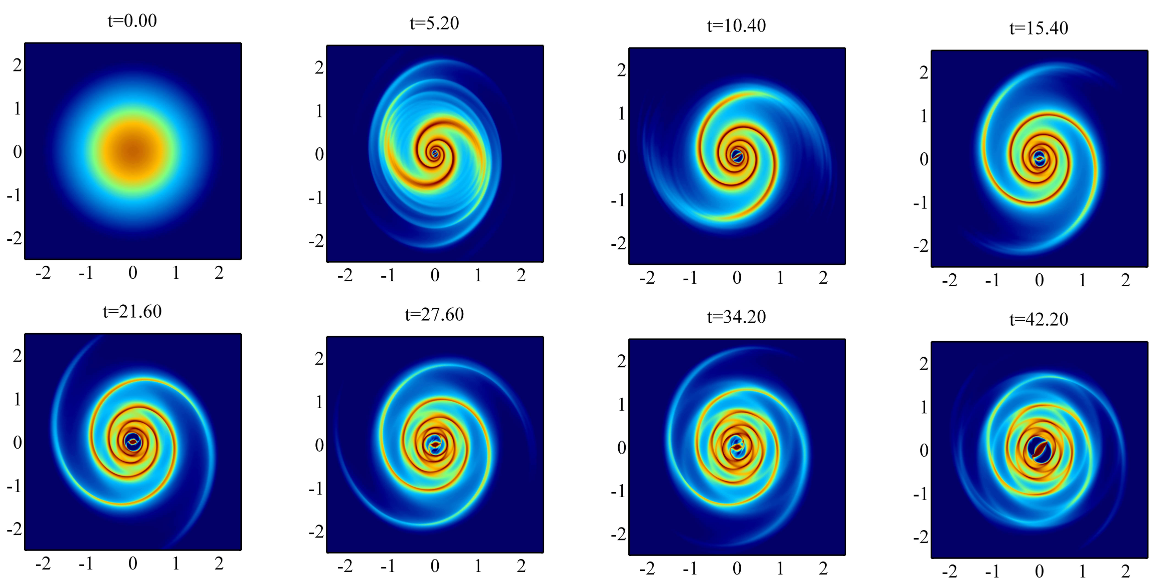


Figure 8: Evolution of gaseous disk submerged into nonaxissymmetric halo

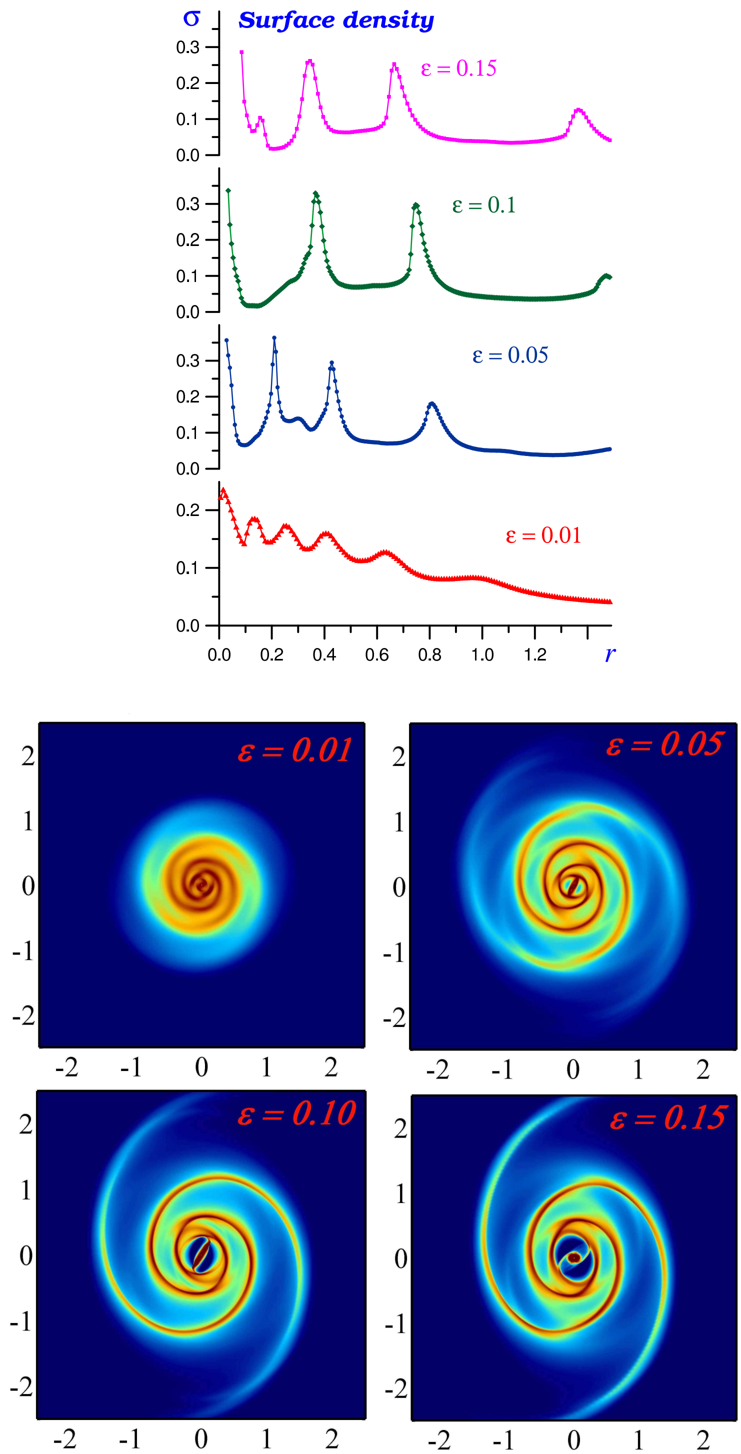


Figure 9: Radial distributions of surface density along azimuth angle $\varphi = 0°$ for models with different ε.

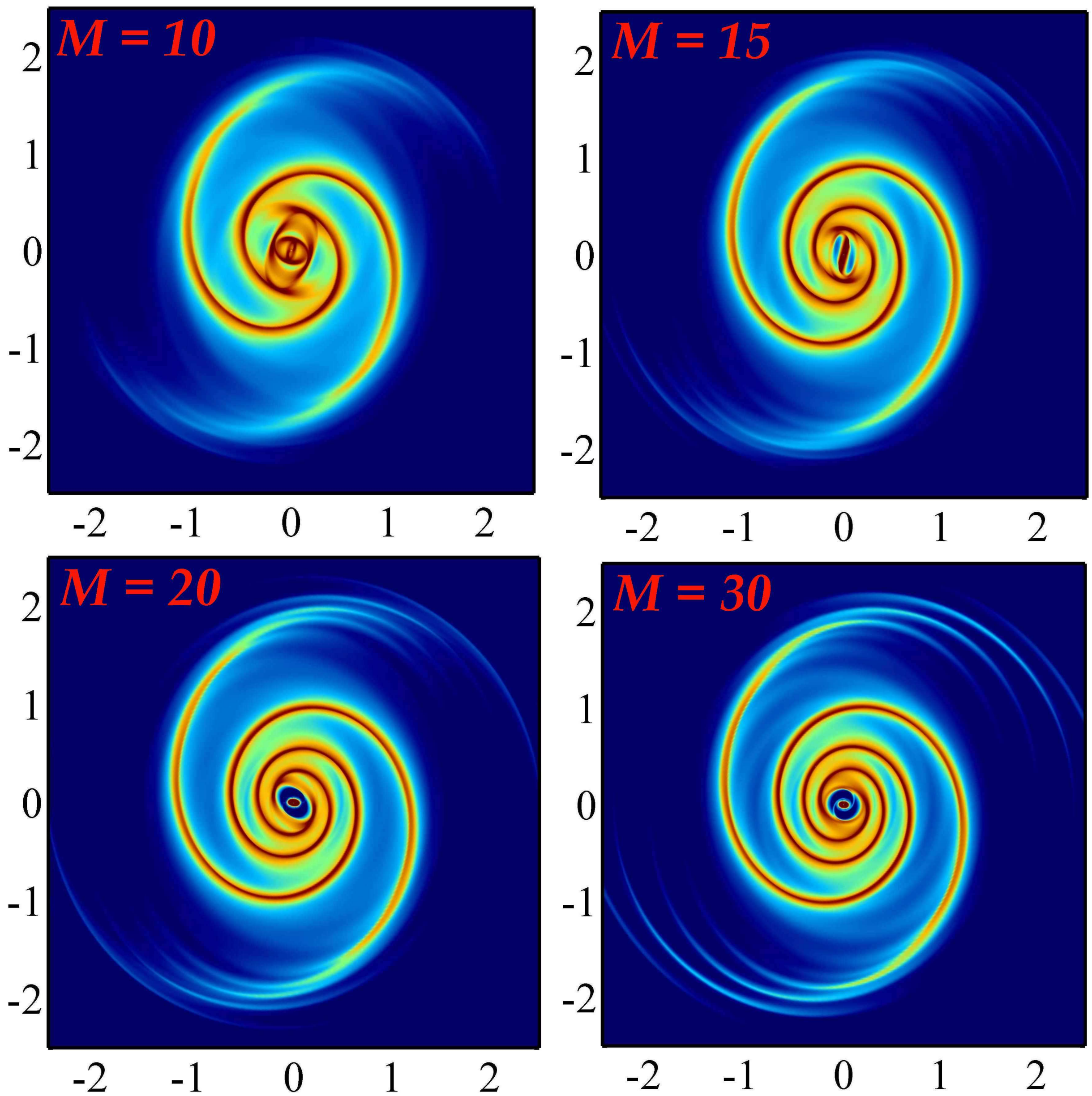


Figure 10: Distributions of surface density in gaseous disks for different values of Mach number M

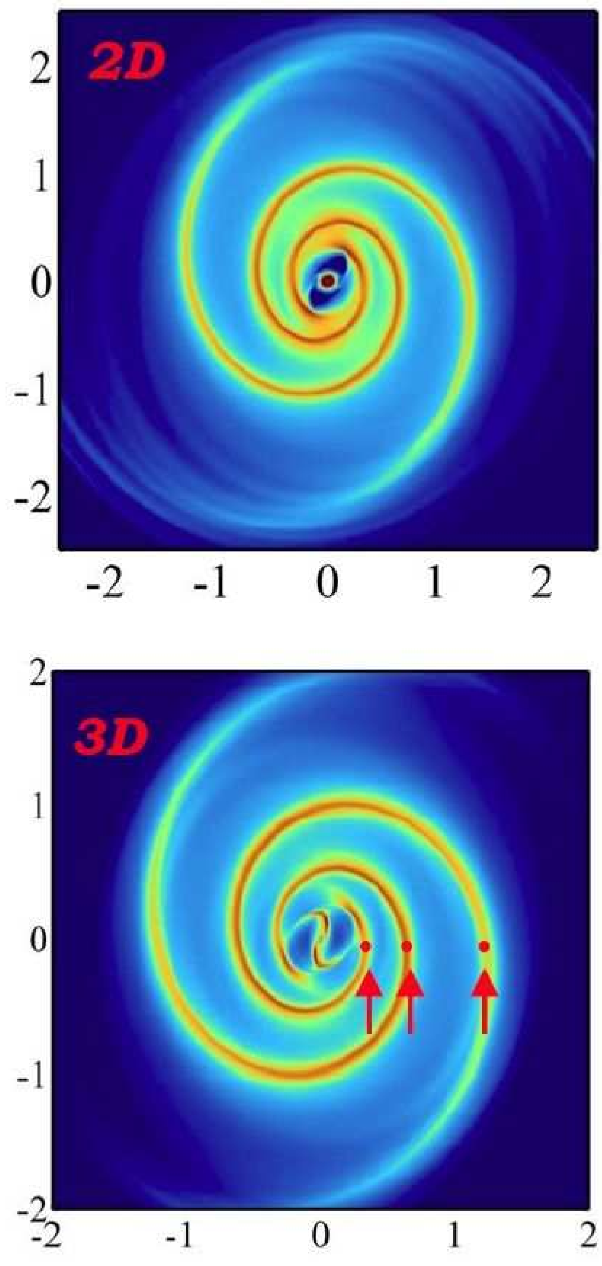


Figure 11: It is a comparison of spiral patterns in 2D and 3D models.

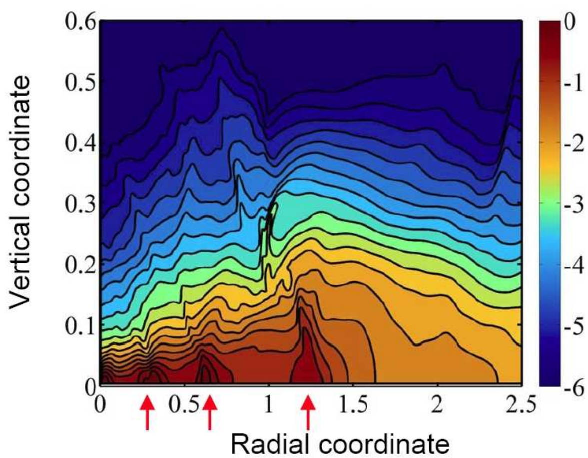


Figure 12: The vertical structure of gaseous disk submerged into triaxial dark halo.